

A *SPITZER*/IRS SPECTRUM OF THE 2008 LUMINOUS TRANSIENT IN NGC 300: CONNECTION TO PROTO-PLANETARY NEBULAE

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ABSTRACT

We present a *Spitzer*/IRS low-resolution mid-infrared spectrum ($5\text{--}14\ \mu\text{m}$) of the luminous transient discovered in the nearby galaxy NGC 300 in May 2008. This transient had peak luminosity $M_V \simeq -13$, showed an optical spectrum dominated by relatively narrow Balmer and Ca II lines in emission, and its progenitor was identified in pre-explosion images as a dust-enshrouded $\sim 10\ M_\odot$ star, characteristics that make it a twin of SN 2008S. The *Spitzer* spectrum, obtained three months after discovery, shows that the transient is very luminous in the mid-IR. Furthermore, the spectrum shows strong, broad emission features at $8\ \mu\text{m}$ and $12\ \mu\text{m}$ that are observed in Galactic carbon-rich proto-planetary nebulae. Combining these data with published optical and near-IR photometry obtained at the same epoch, we find that the mid-IR excess traced by the *Spitzer* spectrum accounts for $\sim 20\%$ of the total energy output. This component can be well explained by emission from $\sim 3 \times 10^{-4}\ M_\odot$ of pre-existing progenitor dust at temperature $T \sim 400\ \text{K}$. The spectral energy distribution of the transient also shows a near-IR excess that can be explained by emission from newly-formed dust in the ejecta. Alternatively, both the near-IR and mid-IR excesses can together be explained by a single pre-existing geometrically thick dust shell. In light of the new observations obtained with *Spitzer*, we revisit the analysis of the optical spectra and kinematics, which were compared to the massive yellow-hypergiant IRC+10420 in previous studies. We show that proto-planetary nebulae share many properties with the NGC 300 transient and SN 2008S. We conclude that even though the explosion of a massive star ($M \gtrsim 10\ M_\odot$) cannot be ruled out, an explosive event on a massive ($M \sim 6\text{--}10\ M_\odot$) carbon-rich AGB/super-AGB or post-AGB star is consistent with all observations of the transients and their progenitors presented thus far.

Subject headings: stars: AGB and post-AGB – stars: circumstellar matter – stars: evolution – stars: winds, outflows – supernovae: individual (SN 2008S)

1. INTRODUCTION

An intriguing luminous optical transient was discovered in the nearby galaxy NGC 300 (hereafter NGC 300-OT) by the amateur astronomer B. Monard on May 14.1, 2008 (Monard 2008). The transient was faint compared to normal core-collapse supernovae, with an absolute magnitude at discovery of $M_V \simeq -13$ (Bond et al. 2008). The optical spectrum obtained by Bond et al. (2008) close to discovery was dominated by relatively narrow Hydrogen Balmer and Ca II lines (infrared triplet and forbidden doublet) in emission, as well as strong Ca II H&K in absorption. Shortly after discovery, Berger & Soderberg (2008) reported strong upper limits on the optical luminosity of the progenitor star obtained from deep archival *HST* data, which led them to suggest that the progenitor was a low-mass main sequence star and the transient was a stellar merger, similar to the red Galactic nova V838 Monocerotis (e.g., Bond et al. 2003).

However, Prieto (2008b) reported the discovery of a luminous mid-infrared (mid-IR) progenitor to the transient in archival *Spitzer* images. The progenitor was a luminous dust-enshrouded star, whose spectral energy distribution

was consistent with a black-body of $R \simeq 300\ \text{AU}$ radiating at $T \simeq 300\ \text{K}$, with $L_{\text{bol}} \simeq 6 \times 10^4\ L_\odot$. This discovery showed that NGC 300-OT was connected to an energetic explosion in a relatively low mass $\sim 10\ M_\odot$ star. The relatively low luminosity of the transient compared to normal core-collapse supernovae, spectral properties, and dust-enshrouded nature of the progenitor star, made NGC 300-OT a “twin” of SN 2008S (Prieto et al. 2008a; Prieto 2008b), which was discovered earlier in 2008 in the galaxy NGC 6946 (Arbour & Boles 2008; Stanishev et al. 2008; Chandra & Soderberg 2008; Steele et al. 2008; Yee et al. 2008; Wesson et al. 2008).

There have been a number of studies of NGC 300-OT and SN 2008S, and the nature of these transients is still under debate (Prieto et al. 2008a; Thompson et al. 2009; Smith et al. 2009; Bond et al. 2009; Berger et al. 2009; Botticella et al. 2009; Wesson et al. 2009; Gogarten et al. 2009; Patat et al. 2009; Kashi et al. 2009). Thompson et al. (2009) present and discuss various possible physical mechanisms that can explain these transients and the likely range of main-sequence masses of the dusty progenitor stars that are consistent with the observations of NGC 300-OT and SN 2008S: (1) massive white-dwarf birth ($M_{\text{ZAMS}} \approx 6\text{--}8\ M_\odot$); (2) electron-capture supernova ($M_{\text{ZAMS}} \approx 9\ M_\odot$); (3) intrinsically low-luminosity iron core-collapse supernova ($M_{\text{ZAMS}} \approx 10\text{--}12\ M_\odot$); and (4) massive star outburst ($M_{\text{ZAMS}} \approx 10\text{--}15\ M_\odot$). Recently, Kashi et al. (2009) proposed a mass transfer event from an extreme-AGB star to a main-sequence star as

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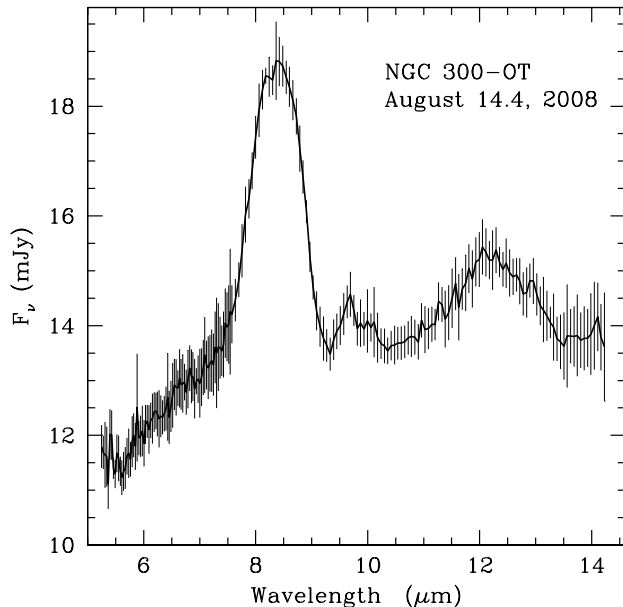


FIG. 1.— Low-resolution *Spitzer*/IRS mid-IR spectrum of the NGC300-OT obtained on 2008 August 14.4, 93 days after the transient was discovered. The vertical error bars are the RMS of each pixel obtained after combining the 20 spectra.

the possible physical mechanism for NGC 300-OT. Any of these potential scenarios suggests that these transients are very important for our understanding of the evolution of stars at the dividing line between “high” and “low” mass (i.e., $8 - 10 M_{\odot}$).

Here we report on a low-resolution mid-IR spectrum of NGC 300-OT obtained with *Spitzer* on August 14, 2008, 93 days after the discovery and 113 days after the first detection (Monard 2008). The transient is luminous in the mid-IR spectral range and shows broad emission features that we interpret as signs of carbon-rich dust, similar to the spectra of carbon-rich proto-planetary nebulae in the Galaxy. The paper is organized as follows. In §2, we discuss the observations and data reduction. In §3, we present the analysis of the spectrum and spectral energy distribution of the transient. In §4, we discuss the implications of our findings. Hereafter we adopt a distance of 1.88 Mpc to NGC 300 (Gieren et al. 2005).

2. SPITZER OBSERVATIONS

We observed NGC 300-OT with the Short-Low (SL; $5.2 - 14 \mu\text{m}$, $R = \Delta\lambda/\lambda = 60 - 120$) module of the Infrared Spectrograph (IRS; Houck et al. 2004) on August 14.4, 2008 (UT). The observations were obtained in staring mode as part of a *Spitzer* Director’s Discretionary Time (DDT) proposal (PID 487; AOR key 28139008). The ramp time was set to 60 sec in both SL orders (SL1: $7.4 - 14 \mu\text{m}$, SL2: $5.2 - 7.5 \mu\text{m}$) and 10 cycles were obtained, for a total exposure time of 1200 sec on source, including the two nod positions, for a total of 20 images.

To reduce the data, we started from the basic calibrated data (BCD) from the *Spitzer* Science Center pipeline (S18.1.0). We constructed a high S/N background image for each order and nod by median combining all the other images. We subtracted the back-

TABLE 1
FEATURES IN THE *Spitzer*/IRS SPECTRUM OF NGC300-OT

λ_c (μm)	Intensity ($10^{-13} \text{ erg cm}^{-2} \text{ s}^{-1}$)	FWHM (μm)
8.33 ± 0.01	2.27 ± 0.20	0.94 ± 0.03
9.71 ± 0.06	0.12 ± 0.11	0.49 ± 0.14
12.16 ± 0.07	0.39 ± 0.14	1.47 ± 0.16

ground from the individual 2D images. Rogue pixels in the background-subtracted images were cleaned with IRSCLEAN (v1.9). We used the routines `profile`, `ridge`, `extract` and `tune` in the *Spitzer* IRS Custom Extractor (SPICE) software package in order to extract flux-calibrated 1D spectra. The spectra of each nod were median combined and the two orders were merged together after applying a small multiplicative correction factor of 3.5% to the SL1 spectra.

Figure 1 shows the final combined spectrum with $\pm 1\sigma$ error bars on the fluxes estimated from the RMS in each pixel. The mean signal-to-noise ratio of the final spectrum is $\simeq 35$ per pixel.

3. ANALYSIS

3.1. Spectral Features

The *Spitzer* spectrum of NGC 300-OT presented in Figure 1 shows two prominent broad emission features at $\approx 8.3 \mu\text{m}$ and $\approx 12.2 \mu\text{m}$. The $8 \mu\text{m}$ flux of the host galaxy at the background pointing positions, measured within the IRS extraction aperture, is $< 1 \text{ mJy}$. Since the $8 \mu\text{m}$ flux of the transient is $\sim 14 \text{ mJy}$ at the time of the IRS spectrum, uncertainties in the subtraction of emission features from polycyclic aromatic hydrocarbons (PAHs) in the host galaxy cannot account for the spectral features we observe. There is also a relatively narrow, but resolved, fainter feature at $\approx 9.7 \mu\text{m}$. The significance of this faint feature is quite uncertain and depends sensitively on the spectra used to obtain the final combined spectrum.

The main properties of the emission features (central wavelength, FWHM, and integrated fluxes) present in the mid-IR spectrum are shown in Table 1. They were obtained after fitting Gaussians to the continuum-subtracted spectrum. The continuum was modeled using a high-order (6th) polynomial fit over the wavelength regions: $\lambda \leq 7.5 \mu\text{m}$, $9.2 - 9.3 \mu\text{m}$, $10.25 - 10.6 \mu\text{m}$, and $\lambda \geq 13.4 \mu\text{m}$. We obtain consistent results if we use a spline function to model the continuum.

In Figure 2 we compare the *Spitzer* spectrum of NGC 300-OT with mid-IR spectra of type IIP supernovae. The spectra of SN 2004et (Kotak et al. 2009) and SN 2005af (Kotak et al. 2006) were obtained from the *Spitzer* archive (PID 237, 20256). Unlike the late-time mid-IR spectra of normal type IIP supernovae (e.g., SN 2004dj, Kotak et al. 2005; SN 2005af, Kotak et al. 2006; SN 2004et, Kotak et al. 2009) and SN 1987A (e.g., Roche et al. 1993; Wooden et al. 1993) that are dominated by narrow fine-structure lines of stable Ni, Ar, Ne, Co, and some molecular SiO in emission at

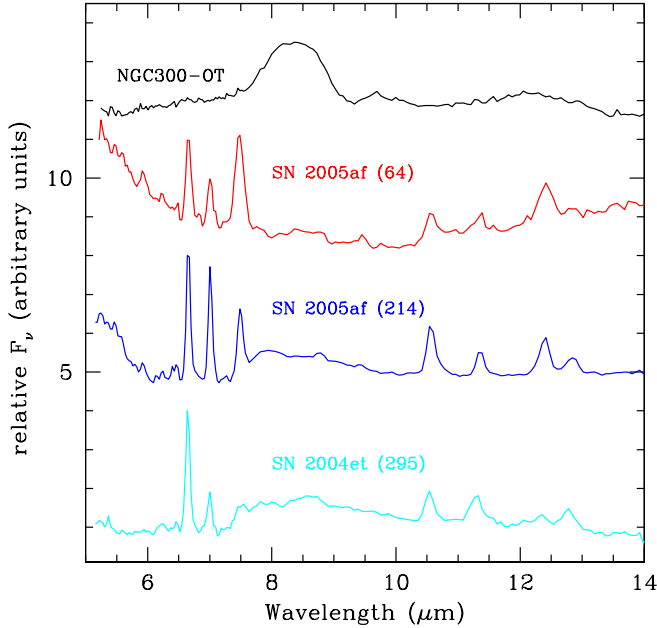


FIG. 2.— Comparison of the *Spitzer*/IRS spectrum of NGC300-OT (top) with mid-IR spectra of the type IIP supernovae SN 2004et and SN 2005af. In parenthesis are the days with respect to the explosion date for each spectrum. We have subtracted a linear continuum fit in the wavelength region shown to each spectrum and scaled the flux arbitrarily.

$\sim 8 - 9 \mu\text{m}$, the mid-IR spectrum of NGC 300-OT presents broad features that are most likely dominated by emission from dust grains in the circumstellar environment. The non-detection of fine-structure lines of Fe-peak elements in emission suggests that the main source of dust heating at this epoch is not the decay of radioactive ^{56}Ni . This is consistent with the low ^{56}Ni production estimated by Botticella et al. (2009) in the case of a supernova explosion.

In Figure 3 we compare the *Spitzer* spectrum of NGC 300-OT with mid-IR spectra of three evolved massive stars that have circumstellar dust. The spectrum of the yellow-hypergiant IRC+10420 (e.g., Humphreys et al. 2002) was obtained from the ISO catalog of SWS spectra (Sloan et al. 2003). The spectra of the yellow-hypergiant M33 Var A (Humphreys et al. 2006) and the LMC B[e] supergiant R66 (Kastner et al. 2006) are from the *Spitzer* archive (PID 5, 3426). The spectra of IRC+10420, M33 Var A and R66 are dominated by the amorphous silicate emission feature at $9.7 \mu\text{m}$, characteristic of oxygen-rich dust. The spectrum of R66 also contains PAH emission features at 6.2 , 7.7 , 8.6 and $11.3 \mu\text{m}$, indicating the presence of carbon-rich dust as well. It is clear from Figure 3 that the mid-IR spectrum of NGC 300-OT does not resemble the spectra of these evolved massive stars with circumstellar dust, even though the optical spectrum of the transient is strikingly similar to IRC+10420 (Bond et al. 2009; see Smith et al. 2009 for the case of SN 2008S).

In Figure 4 we compare the spectrum of NGC 300-OT with mid-IR spectra of Galactic proto-planetary nebulae (pPNe). Two of the pPNe have carbon-rich dust (IRAS 20000+3239 and IRAS 13416-6243) and

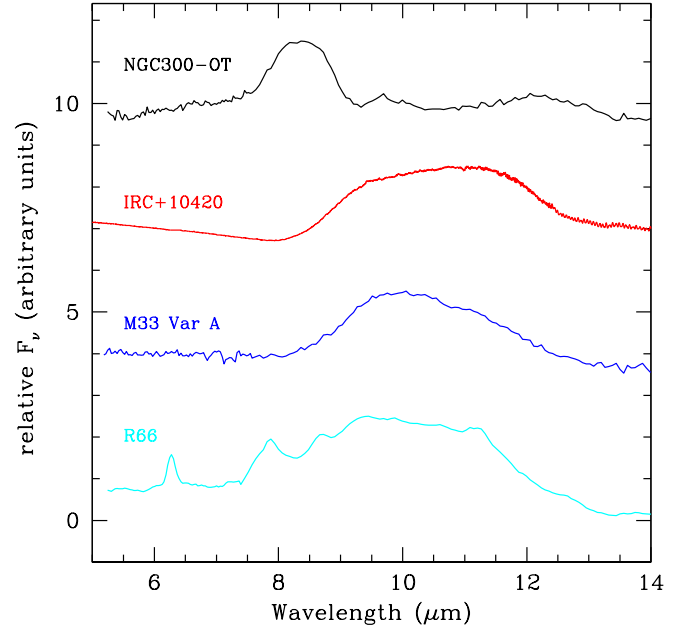


FIG. 3.— Comparison of the *Spitzer*/IRS spectrum of NGC300-OT (top) with mid-IR spectra of evolved massive stars that show circumstellar dust emission. These include the yellow-hypergiants IRC+10420 and M33 Var A, and the B[e] supergiant R66. We have subtracted a linear continuum fit in the wavelength region shown to each spectrum and scaled the flux arbitrarily.

the others have oxygen-rich dust (IRAS 15452-5459 and IRAS 17150-3224). The spectra are all from the ISO/SWS catalog (Sloan et al. 2003). The spectra of oxygen-rich pPNe contain SiO absorption at $7.9 \mu\text{m}$ and a strong silicate absorption feature at $9.7 \mu\text{m}$, which do not appear to be present in the spectrum of NGC 300-OT. Also the central wavelengths and FWHM of the two “bumps” at $\sim 8.5 \mu\text{m}$ and $\gtrsim 12 \mu\text{m}$ are inconsistent with the features in the spectrum of NGC 300-OT.

The spectrum of NGC 300-OT is most similar to the spectra of the carbon-rich pPNe in Figure 4. They contain broad emission features at $\sim 8 \mu\text{m}$ and $\sim 12 \mu\text{m}$, which have been associated with C-C and C-H bending and stretching modes identified as the carriers of PAHs (e.g., Duley & Williams 1981; Peeters et al. 2002). Note, however, that the spectrum of NGC 300-OT does not contain the $6.2 \mu\text{m}$ PAH feature that is clearly present in the two carbon-rich pPNe. We can put a 3σ upper limit on the integrated flux of the $6.2 \mu\text{m}$ PAH feature of $I_{6.2} < 2.1 (\text{FWHM}/0.2 \mu\text{m}) \times 10^{-14} \text{ erg cm}^{-2} \text{ s}^{-1}$. This gives a 3σ limit on the flux ratio of $I_{6.2}/I_{8.3} < 0.09$ for an assumed FWHM = $0.2 \mu\text{m}$. The spectrum of IRAS 20000+3239 also has the $6.9 \mu\text{m}$ PAH feature, which is not present in the spectrum of NGC 300-OT. We can put a 3σ upper limit on the integrated flux of the $6.9 \mu\text{m}$ PAH feature of $I_{6.9} < 1.9 (\text{FWHM}/0.2 \mu\text{m}) \times 10^{-14} \text{ erg cm}^{-2} \text{ s}^{-1}$, which gives a limit on the flux ratio $I_{6.9}/I_{8.3} < 0.08$ for an assumed FWHM = $0.2 \mu\text{m}$.

3.2. Spectral Energy Distribution

We can construct the full spectral energy distribution (SED) of NGC 300-OT at the epoch of the *Spitzer* spectrum using the optical and near-IR photometry presented

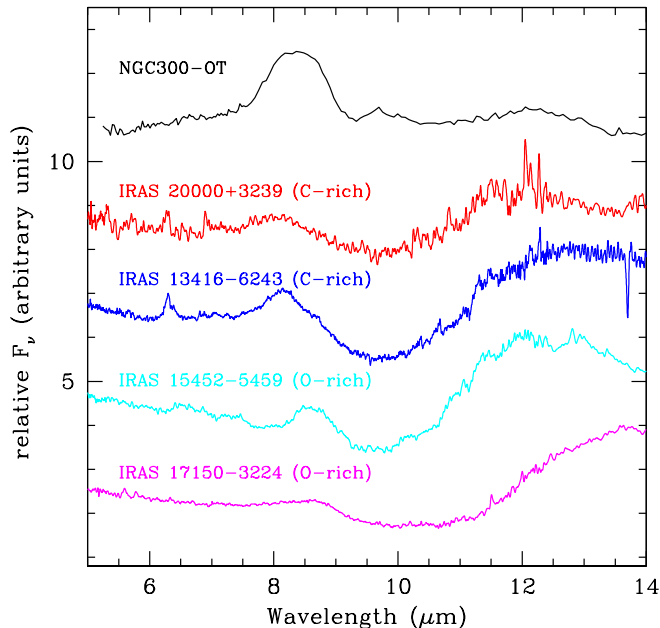


FIG. 4.— Comparison of the *Spitzer*/IRS spectrum of NGC300-OT (top) with mid-IR spectra of Galactic proto-planetary nebulae. The pPNe have different dust chemistry: carbon-rich (IRAS 2000+3239 and IRAS 13416-6243) and oxygen-rich (IRAS 1545-549 and IRAS 17150-3224) dust. We have subtracted a linear continuum fit in the wavelength region shown to each spectrum and scaled the flux arbitrarily.

in Bond et al. (2009). Figure 5 shows the optical to mid-IR SED of the transient 93 days after the discovery date. We have corrected all the fluxes for a total extinction along the line-of-sight of $E(B - V) = 0.25$ mag, which is the mean of the extinction values reported in Bond et al. (2009). We assume $R_V = 3.1$ and use the Schlegel et al. (1998) reddening law, with $A_\lambda \propto \lambda^{-1.6}$ in the near-to-mid infrared range. The *filled circles* are the optical (*BVR*) and near-IR (*JHK*) fluxes from Bond et al. (2009). The thick line is the *Spitzer* mid-IR spectrum. For comparison, we show the SED of the luminous dust-enshrouded progenitor of NGC 300-OT (*filled squares*) obtained from pre-explosion *Spitzer* IRAC (3.6 – 8 μ m) and MIPS (24 μ m) photometry (see Table 2; these data were used in Thompson et al. 2009 and Bond et al. 2009). At the epoch of the *Spitzer* observation the transient is ~ 20 times more luminous than the progenitor at 8 μ m. The results of black-body fits to the transient and progenitor SED using dust emissivity law $Q_\lambda \propto \lambda^{-n}$ ($n = 0, 1$) are presented in Table 3.

The evolution of the light curves of NGC 300-OT in different filters presented by Bond et al. (2009) shows that the transient becomes redder in time, with the color evolving from $V - K \simeq 3.1$ mag at discovery to $V - K \simeq 5.2$ mag at the time of the *Spitzer* spectrum. This fast evolution in the $V - K$ color, while the $B - V$ color only changes from $\simeq 0.8$ mag to $\simeq 1.1$ mag in the same time period, suggests the presence of warm circumstellar dust formed in the explosion or heated pre-existing dust.

Botticella et al. (2009) analyzed the SED of SN 2008S and showed that the evolution in optical+near-IR fluxes could be explained with a single “hot” black-body un-

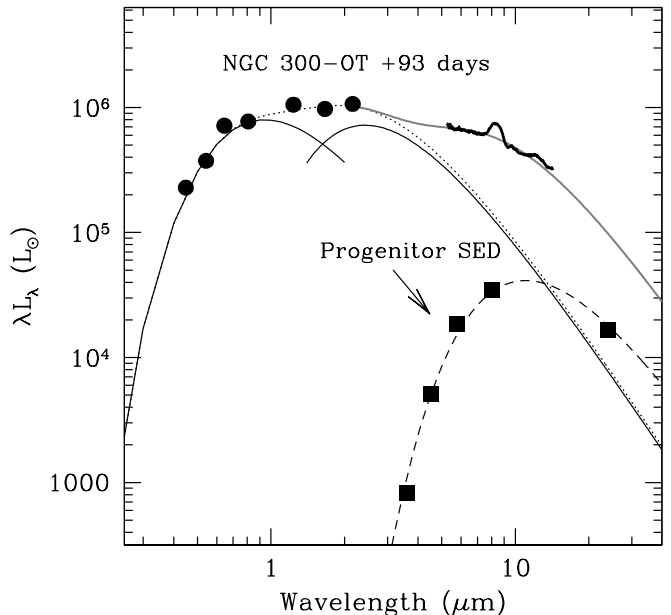


FIG. 5.— SED of NGC 300-OT at 93 days after discovery. The *filled circles* are the optical (*BVR*) and near-IR (*JHK*) fluxes of NGC 300-OT from Bond et al. (2009). The *Spitzer*/IRS spectrum is shown as the *thick black line*. The *dotted line* is a fit to the optical+near-IR SED of the transient using the sum of two black-bodies with temperatures $T_1 \approx 3890$ K and $T_2 \approx 1500$ K. The *grey line* is an extension of the previous black-body fits to mid-IR by adding a cooler component with $T_3 \approx 485$ K. We show the SED of the progenitor of NGC 300-OT for comparison (*filled squares*). The *dashed line* is a single black-body fit with $T \approx 335$ K to the progenitor SED.

til ~ 120 days after explosion, but they needed a second “warm” black-body component at later times. They concluded that the near-IR flux excess of SN 2008S at $\gtrsim 120$ days after explosion was possibly due to newly-formed dust in the ejecta or shock-heated dust in the circumstellar environment.

As in the case of SN 2008S, we find that the *BVRJHK* fluxes of NGC 300-OT at 93 days after discovery (113 days after the first detection⁵) can be well-fit by the sum of two black-bodies ($\chi_\nu^2 = 1.8$), a hot component with $T_1 = 3893$ K, $R_1 = 10.7$ AU and a warm component with $T_2 = 1511$ K, $R_2 = 67.3$ AU (see the dotted line in Figure 5). The total luminosity of these components is $2.1 \times 10^6 L_\odot$. A modified black-body with dust emissivity $Q_\lambda \propto \lambda^{-1}$ for the colder component gives $T_1 = 3870$ K, $T_2 = 1256$ K, and comparable total luminosity. However, the mid-IR SED of NGC 300-OT traced by the *Spitzer* spectrum is a factor of $\sim 2 - 9$ brighter between 5 – 14 μ m than the extrapolated sum of the two black-bodies. We add a third black-body component with lower temperature, while keeping the fit to the optical and near-IR fluxes fixed, to account for the mid-IR excess. We find a good fit ($\chi_\nu^2 = 1.5$) to the continuum of the *Spitzer* spectrum (defined in §3.1) with $T_3 = 485$ K and $R_3 = 515$ AU. The luminosity of this component is

⁵ We assume this is a good estimate of the time after explosion. This seems like a reasonable assumption given that the light curve of the transient is rising fast at that time (see Figure 1 in Bond et al. 2009).

TABLE 2
SPECTRAL ENERGY DISTRIBUTION OF THE PROGENITOR OF
NGC 300-OT

λ	λF_λ (10^{-14} erg cm $^{-2}$ s $^{-1}$)	Telescope/Instrument
3.6 μ m	0.75 ± 0.15	<i>Spitzer</i> /IRAC
4.5 μ m	4.67 ± 0.43	<i>Spitzer</i> /IRAC
5.8 μ m	16.83 ± 1.10	<i>Spitzer</i> /IRAC
8.0 μ m	31.49 ± 1.67	<i>Spitzer</i> /IRAC
24 μ m	15.03 ± 1.37	<i>Spitzer</i> /MIPS

$6.0 \times 10^5 L_\odot$, which is 29% of the optical+near-IR luminosity and 22% of the total integrated luminosity of the transient. A modified black-body with dust emissivity $Q_\lambda \propto \lambda^{-1}$ gives $T_3 = 394$ K and total luminosity $6.4 \times 10^5 L_\odot$.

The two black-body components that can reproduce the near-IR and mid-IR excesses in the SED of NGC 300-OT are likely due to emission from circumstellar dust. The hotter component ($T_2 = 1511$ K) can be reasonably explained with newly formed dust in the ejecta, as proposed by Botticella et al. (2009) for SN 2008S. The velocity inferred from the black-body radius $R_2 = 67$ AU and the time after the first detection of the transient is ~ 1000 km s $^{-1}$. This velocity is in the range of velocities measured from emission lines in the optical spectra of NGC 300-OT of $\sim 100 - 1000$ km s $^{-1}$ (Bond et al. 2009; Berger et al. 2009).

Another way to explain this warm dust component would be emission from pre-existing progenitor dust, although this seems less likely because of dust destruction from the initial outburst light (e.g., Dwek 1983). Assuming a luminosity at maximum light of $L_{\max} \approx 5 \times 10^6 L_\odot$ (luminosity at discovery) and a dust sublimation temperature of $T_{\text{sub}} \simeq 1500$ K, we obtain a radius for the dust-free cavity of $\sim 80 - 250$ AU depending on the assumed dust emissivity law, $Q_\lambda \propto \lambda^0 - \lambda^{-1}$. This radius is a factor of $\sim 1.2 - 3.7$ times larger than the black-body scale R_2 of the ~ 1500 K temperature dust, which suggest the near-IR emitting dust may have been formed in the ejecta.

We can estimate the total dust mass needed to account for the luminosity of the warm black-body component using equation (4) in Dwek et al. (1983) and assuming an average carbon grain density of $\rho_{\text{dust}} \simeq 2.24$ g cm $^{-3}$,

$$M_d \approx 2 \times 10^{-6} \left(\frac{T_d}{1000 \text{ K}} \right)^{-5} \left(\frac{L_d}{10^6 L_\odot} \right) M_\odot \quad (1)$$

where T_d is the dust temperature in Kelvin, and L_d is the dust luminosity in L_\odot . This equation assumes that the dust grains have an absorption/emission efficiency of $Q_\lambda \propto \lambda^{-1}$. Using T_2 and L_2 for $n = 1$ in Table 3, we obtain $M_d \approx 10^{-6} M_\odot$ for the mass of newly formed dust at 93 days after discovery. We can compare this dust mass to that in SN 2008S. Under the same assumptions about dust properties considered in equation (1), this dust mass is ~ 7 times larger than was needed to explain the near-

TABLE 3
BLACK-BODY FITS TO THE TRANSIENT
AND PROGENITOR SEDs

Parameter	Value ^a ($n = 0$)	Value ^a ($n = 1$)
NGC 300-OT <i>BVRIJHK</i> fluxes		
T_1 (K)	3893	3870
R_1 (AU)	10.7	...
L_1 (L_\odot)	1.1×10^6	1.1×10^6
T_2 (K)	1511	1256
R_2 (AU)	67.3	...
L_2 (L_\odot)	9.8×10^5	8.2×10^5
NGC 300-OT adding fit to <i>Spitzer</i> data		
T_3 (K)	485	394
R_3 (AU)	515	...
L_3 (L_\odot)	6.0×10^5	6.4×10^5
Progenitor SED		
T (K)	335	281
R (AU)	332	...
L (L_\odot)	5.7×10^4	5.4×10^4

^aBlack-body fits with dust emissivity law $Q_\lambda \propto \lambda^{-n}$.

IR excess in SN 2008S ~ 120 days after explosion (using the data in Table 8 of Botticella et al. 2009).

The mid-IR excess revealed by the *Spitzer* spectrum of NGC 300-OT cannot be explained by newly formed dust. The constant expansion velocity needed to reach a black-body radius of $R_3 = 515$ AU at this epoch is $v \sim 8000$ km s $^{-1}$, far larger than the velocities observed in the optical spectra of the transient. This component must be emission from pre-existing dust from the progenitor. Dust grains that were not destroyed by the initial outburst will absorb the outburst light, warm up, and re-radiate at mid-IR wavelengths. Using equation (1) we estimate that a dust mass of $M_d \approx 3 \times 10^{-4} M_\odot$ and dust optical depth of $\tau_V \approx 0.4$ is needed to account for the mid-IR excess, assuming dust emissivity with $n = 1$ in Table 3. For a gas-to-dust mass ratio of 200 that is consistent with observations of evolved stars with carbon-rich dust in the LMC (e.g., Matsuura et al. 2009), we find a gas mass of $\approx 0.06 M_\odot$. A similar mass of dust of $\sim 10^{-4} M_\odot$ is needed to explain the SED of the progenitor of NGC 300-OT, suggesting that a substantial fraction of the dust in the progenitor wind survives the explosion. Interestingly, a similar mass of dust is also needed to explain the mid-IR excess observed in SN 2008S ~ 17 days after explosion (Botticella et al. 2009).

We performed radiation transport calculations using DUSTY (Ivezic & Elitzur 1997) to check if the SED of NGC 300-OT can also be explained by radiation through a spherical shell of dust. We found a reasonable fit to the optical to mid-IR SED using a central black-body with $T = 4000 - 5000$ K illuminating a dust shell with density profile $\rho(r) \propto r^{-1}$, inner and outer radius of the shell $R_{\text{in}} \simeq 100$ AU and $R_{\text{out}} \simeq 10000$ AU, temperature of the dust at the inner radius $T = 1500$ K, and dust optical depth $\tau_V \simeq 1.2$. We note that this solution is not unique since we also obtain a reasonable fit to the SED with $\rho(r) = \text{constant}$, $R_{\text{in}} \simeq 100$ AU, and $R_{\text{out}}/R_{\text{in}} \sim 10$, with all the other parameters being equal. Wesson et al. (2009) analyzed the optical to mid-IR SED of the progenitor of SN 2008S and the transient ~ 17 days and ~ 180 days after explosion using a radiative transfer code.

They find that the SED of SN 2008S can be explained with a central source illuminating a spherical dust shell with density profile $\rho \propto r^{-2}$, inner radius $R_{\text{in}} \simeq 1250$ AU, and $\tau_V \simeq 0.8$, where $\gtrsim 98\%$ of the pre-existing progenitor dust ($M_{\text{dust}} \simeq 1.2 \times 10^{-5} - 3.5 \times 10^{-3} M_{\odot}$, depending on R_{out}) survives the explosion. This is qualitatively similar to our results for NGC 300-OT.

4. DISCUSSION & CONCLUSIONS

We have presented a low-resolution mid-IR spectrum of NGC 300-OT obtained with *Spitzer* on August 14.4, 2008, 93 days after the discovery of the transient. We now give our discussion and interpretation of the results.

4.1. Mid-IR Spectrum and SED of NGC 300-OT

The mid-IR spectrum of NGC 300-OT shows broad emission features at $8.3 \mu\text{m}$ and $12.2 \mu\text{m}$ that are similar to the broad features seen in the spectra of carbon-rich pPNe in the Galaxy (e.g., Kwok 1993; Kwok et al. 2001), called “Class C” PAH sources by Peeters et al. (2002). Joblin et al. (2008) derive profiles for the broad $8 \mu\text{m}$ and $12 \mu\text{m}$ features from the spectrum of the archetypal “Class C” PAH source, the pPN IRAS 13416-6243 (see Figure 4). These broad features are attributed to hydrocarbons with a predominantly aliphatic nature, which undergo photochemical processing in proto-planetary nebula to transform into the more aromatic material observed in carbon-rich planetary nebulae (e.g., Kwok et al. 2001; Sloan et al. 2007). Joblin et al. (2008) show that these broad features are also observed in young planetary nebulae, and are distinct from the spectral features of neutral PAHs, ionized PAHs, and very small grains.

It is interesting to note that the position of the center of the PAH complex at $7 - 8 \mu\text{m}$, observed in many astrophysical environments including the ISM and evolved stars (e.g., Tielens 2008 and references therein), has been shown to correlate with the effective temperature of the host star in Herbig A/Be stars, planetary-nebulae, and pPNe (e.g., Sloan et al. 2007; Keller et al. 2008; Boersma et al. 2008). The correlation goes in the sense that stars with lower effective temperatures (i.e., weaker UV-optical radiation field) show the central peak of this complex at longer wavelengths. The central wavelength at $8.3 \mu\text{m}$ detected in the *Spitzer* spectrum of NGC 300-OT would imply an effective temperature of ~ 4000 K (see Fig. 8 in Keller et al. 2008), which is consistent with the temperature of the hot black-body ($T \simeq 3900$ K) derived from the optical SED of the transient. This provides indirect and independent support for our interpretation of the mid-IR spectrum, and also evidence that UV processing has not yet converted predominantly aliphatic hydrocarbons into PAHs in NGC 300-OT.

A noteworthy difference between the *Spitzer* spectrum of NGC 300-OT and the spectra of carbon-rich pPNe is the non-detection of the $6.2 \mu\text{m}$ PAH emission feature to fairly deep limits. In the carbon-rich pPN IRAS 13416-6243, for example, the ratio of the integrated fluxes of the $6.2 \mu\text{m}$ and $8 \mu\text{m}$ features is $I_{6.2}/I_8 \simeq 0.13$, which is a factor of 1.3 higher than the 3σ limit for NGC 300-OT. The $6.2 \mu\text{m}$ emission feature is thought to be produced by the C-C stretching mode in ionized PAHs. The astronomical and laboratory spectra of PAHs and PAH-like molecules show such a wide variety that the absence

of the $6.2 \mu\text{m}$ feature may be explained by differences in shape, ionization state, impurities, and size of the molecules (e.g., Pathak & Rastogi 2008; Bauschlicher et al. 2009). On the other hand, the non-detection of the $6.9 \mu\text{m}$ PAH emission feature in the spectrum of NGC 300-OT seems to be consistent with the integrated flux of this feature measured in some Galactic carbon-rich pPNe like IRAS 20000+3239. This emission feature is thought to be associated with aliphatic material (C-H bending mode) and is detected only in a fraction of pPNe (e.g., Kwok et al. 1999).

The mid-IR excess traced by the *Spitzer* spectrum can be well explained by the presence of warm circumstellar dust ($T \sim 400$ K) with mass $M_d \sim 3 \times 10^{-4} M_{\odot}$. This dust was most likely part of the dusty progenitor wind, pre-existing the luminous explosion that produced the optical transient. The SED of NGC 300-OT at the epoch of the *Spitzer* spectrum also shows a near-IR excess, which can be explained with a small mass ($\sim 10^{-6} M_{\odot}$) of warm circumstellar dust ($T \sim 1300$ K) formed in the ejecta.

Alternatively, the SED of NGC 300-OT can be reasonably well explained with a $T = 4000 - 5000$ K black-body illuminating a spherical shell of pre-existing progenitor dust that extends from ~ 100 AU to ~ 10000 AU, where the inner radius of the dust shell marks the destruction of dust by the initial outburst light. The presence of a substantial mass of pre-existing dust from the progenitor wind in the overall SED of NGC 300-OT was also characteristic of SN 2008S (Wesson et al. 2009) and indicates that most of the dust survived the explosion.

4.2. NGC 300-OT and SN 2008S: Connection to Proto-Planetary Nebulae

The similarity of the mid-IR spectrum of NGC 300-OT with carbon-rich pPNe is very striking and may shed new light on the nature of this transient, SN 2008S, and the other optical transients (e.g., SN 1999bw, M85-OT) that show similar characteristics and appear to be part of the same class (Prieto et al. 2008c; Thompson et al. 2009). The optical spectra of NGC 300-OT and SN 2008S transients were compared with the spectrum of the massive Galactic yellow-hypergiant star IRC+10420 (Smith et al. 2009; Bond et al. 2009; Berger et al. 2009), which shows an F-type supergiant spectrum with Balmer lines in emission, as well as strong Ca II triplet, [Ca II] doublet, and [Fe II] lines in emission. Given the similarity of the mid-IR spectrum of NGC 300-OT with pPNe, we have searched in the literature for their optical spectra. We found several examples of pPNe with optical spectra that are remarkably similar to NGC 300-OT and SN 2008S. In the sample of echelle long-slit spectra of evolved stars of Sánchez Contreras et al. (2008), the Galactic pPNe IRAS 17516-2525 (O-B spectral type), M1-92 (B2-F5), Hen 3-1475 (Be), IRAS 22036+5306 (F4-7), and IRAS 08005-2356 (F4 Ie) show Balmer lines and also strong Ca II triplet and [Ca II] doublet in emission. Other examples can be found in the atlas of optical spectra of post-AGB stars presented in Suárez et al. (2006). The presence of forbidden Ca II in emission in the spectra of NGC 300-OT and SN 2008S, pPNe, and IRC+10420, which is rarely present in stellar spectra, means that calcium is not depleted onto dust grains, most likely due to the destruction of grains by relatively fast shocks (e.g.,

Hartigan et al. 1987).

Another similarity between NGC 300-OT and pPNe is revealed by the kinematics and the detection of double-peaked Balmer and Ca II triplet lines in the spectrum of NGC 300-OT. Bond et al. (2009) interpreted these double features as the presence of a bipolar outflow with an expansion velocity of $\approx 75 \text{ km s}^{-1}$, and possibly faster components moving at $\sim 200 \text{ km s}^{-1}$. Berger et al. (2009) discussed evidence for even faster velocity components (including inflow) going up to $\sim 1000 \text{ km s}^{-1}$. Aspherical winds or outflow moving at velocities of a few $\times 100 \text{ km s}^{-1}$ up to $\sim 1000 \text{ km s}^{-1}$ are observed in pPNe (e.g., Balick & Frank 2002). Multiple studies using high-resolution imaging of Galactic pPNe with *HST* have shown a variety of complex morphologies, with bipolar, multipolar and point-symmetric structures (e.g., Sahai et al. 1999). In particular the pPN Hen 3-1475 (also classified as a young PN in some studies), which is in the spectroscopic sample of Sánchez Contreras et al. (2008) and whose spectrum shares many features with the spectra of NGC 300-OT, has a bipolar morphology and velocity components up to $\sim 1200 \text{ km s}^{-1}$ (e.g., Riera et al. 1995, 2003). Given the inferred luminosity of $\sim 10^4 L_{\odot}$, chemistry, and kinematics, Riera et al. (1995, 2003) proposed that Hen 3-1475 was a relatively high-mass star ($\sim 3 - 5 M_{\odot}$) in the post-AGB phase of evolution. Another interesting example is the Red Rectangle, an extensively studied intermediate-mass pPNe with carbon-rich dust chemistry and a fast ($\sim 560 \text{ km s}^{-1}$) bipolar outflow traced by H α in emission (e.g., Witt et al. 2009).

Several studies have proposed that SN 2008S and NGC 300-OT were the result of an energetic eruption in a dust-enshrouded $10 - 20 M_{\odot}$ star, where the star survives the eruption. Smith et al. (2009) discussed a super-Eddington wind as the physical mechanism that produced SN 2008S, similar to the super-outbursts of massive LBVs (e.g., van Marle et al. 2008). Berger et al. (2009) presented possible observational evidence for this model from the complex kinematics that they inferred from their high-resolution spectra of NGC 300-OT. Bond et al. (2009) did not require that the progenitor of the transient was LBV-like, but rather an OH/IR star (e.g., Wood et al. 1992) that was evolving to warmer temperatures (in a blue-loop) at the time of the eruption. These studies relied heavily on comparing the optical spectra of the transients with the spectrum of the massive yellow-hypergiant IRC+10420 (e.g., Humphreys et al. 2002; Davies et al. 2007). However, as discussed here, there are examples of pPNe in the Galaxy that share very similar optical spectroscopic characteristics with NGC 300-OT and SN 2008S. In fact, the complex model of inflow-outflow put forth in Berger et al. (2009) to explain the spectra of NGC 300-OT has been discussed in the context of fast winds of AGB and post-AGB stars in binaries (Soker 2008).

Finally, in a mid-IR study of massive stars in the LMC, Bonanos et al. (2009) argued that B[e] supergiants (e.g., R66 in Figure 3) may share a common origin with NGC 300-OT and SN 2008S. Supergiant B[e] stars in the LMC are very rare (only ~ 10 discovered), have luminosities $L_{\text{bol}} \gtrsim 10^4 L_{\odot}$, and dusty circumstellar envelopes, properties that are broadly consistent with the proper-

ties of the progenitors of NGC 300-OT and SN 2008S. However, the circumstellar dust around B[e] supergiants in the LMC is significantly hotter ($\gtrsim 800 \text{ K}$) than the dust around the progenitors, probably because they are oxygen-rich.

In summary, we have shown that NGC 300-OT and SN 2008S have several properties (mid-IR spectrum, optical spectra, kinematics, and dusty circumstellar medium) that are characteristic of pPNe in the Galaxy; they are not unique to massive stars like IRC+10420.

4.3. The Progenitors of NGC 300-OT and SN 2008S: Massive Carbon-rich AGB/post-AGB stars ?

The progenitors of NGC 300-OT and SN 2008S were luminous ($\sim 4 - 6 \times 10^4 L_{\odot}$) dust-enshrouded stars with warm ($T \sim 300 - 450 \text{ K}$) circumstellar dust, found at the red extremum of the AGB sequence in a mid-IR color-magnitude diagram (Thompson et al. 2009). They are part of the extreme-AGB (EAGB) sequence, which has been identified as a continuation of the AGB to redder mid-IR colors in resolved stellar population studies of nearby galaxies using *Spitzer* (e.g., LMC, Blum et al. 2006; M33, Thompson et al. 2009). Their location in the mid-IR color-magnitude diagram indicates extreme mass-loss and relatively cool circumstellar dust (e.g., Srinivasan et al. 2009). Interestingly, Matsuura et al. (2009) find that most EAGB stars in the LMC sample for which they have obtained mid-IR spectra have carbon-rich dust, which is consistent with the evidence presented here for carbon-rich dust in NGC 300-OT. Even though the number of carbon-rich AGBs in the LMC declines as a function of luminosity with respect to oxygen-rich AGBs, interpreted as evidence of Hot-Bottom-Burning which converts carbon into nitrogen and oxygen, there are carbon stars with luminosities approaching those of the progenitors of NGC 300-OT and SN 2008S (e.g., van Loon et al. 1998; Frost et al. 1998). One example is IRAS 05278-6942, a carbon-rich AGB star in the LMC that has $L_{\text{bol}} \sim 4 \times 10^4 L_{\odot}$ and $\dot{M} \sim 3 \times 10^{-5} M_{\odot} \text{ yr}^{-1}$ (Groenewegen et al. 2007). Indeed, Kastner et al. (2008) in their study of the most luminous $8 \mu\text{m}$ sources in the LMC, point out that “more high- L_{bol} carbon stars may lurk among the very red, unclassified objects” in their sample.

The high-mass counterparts of AGB stars with $M_{\text{ZAMS}} \simeq 8 - 10 M_{\odot}$, so-called super-AGB stars, have been proposed as good candidates for the progenitors of NGC 300-OT and SN 2008S (see Thompson et al. 2009 and references therein; Botticella et al. 2009). These stars end up with an O-Ne core and, depending on the competing effects of core-growth after carbon ignition and strong mass-loss, they can explode as electron-capture supernovae in a narrow and uncertain mass range around $\sim 9 M_{\odot}$ or end-up as O-Ne white dwarfs at lower masses (e.g., Nomoto 1984; Poelarends et al. 2008). The luminosities of SAGB stars in theoretical models can reach $\sim 10^5 L_{\odot}$ at the end of their evolution (e.g., Siess 2007), comparable to the luminosities of the progenitors of NGC 300-OT and SN 2008S. These models also predict that the photospheric abundances of SAGB stars should be oxygen-rich ($\text{C/O} < 1$) at the end of their evolution, through a combination of Hot-Bottom-Burning and the occurrence of the third dredge-up. However, the

modeling of these processes in the AGB and SAGB evolution is very uncertain and depends on several important factors like metallicity, the treatment of convection, mass-loss, and the input opacities (e.g., Marigo 2008). In fact, there are theoretical studies that have discussed the possibility of carbon-rich photospheres in massive AGBs (e.g., Nomoto 1987; Marigo 2007).

An important difference between the progenitors of the luminous transients and carbon-rich AGB and EAGB stars is that they did not show variability in the mid-IR within 3 – 4 years of explosion (Prieto et al. 2008b; Thompson et al. 2009), whereas most AGB and EAGB stars are highly variable (e.g., Gronewegen et al. 2007; Vijn et al. 2009). Since variability in AGB stars is explained by pulsations that drive the mass-loss (thermal pulses), the lack of variability in the progenitors may indicate that they were at the very tip of the AGB or SAGB phase before the explosion, perhaps past a *super-wind* phase. If this is the case, the progenitor could be classified as a pPN (i.e., it was in the post-AGB phase at the time of the explosion).

4.4. Progenitors and Transients: Concluding Remarks

The physical mechanism that produced the energetic explosions ($\sim 2 - 6 \times 10^{47}$ erg in optical to near-IR light) of NGC 300-OT and SN 2008S is still unknown. Although the observations presented here do not directly shed light on the mechanism that produced the transients, we have shown that all the observations of the transients and their progenitors presented thus far are consistent with the explosion of a massive ($M_{\text{ZAMS}} \sim 6 - 10 M_{\odot}$), carbon-rich AGB, super-AGB or post-AGB star, either single or in a binary. An in-depth discussion of some of the mechanisms that could explain the transients can be found in Thompson et al. (2009). Here we briefly comment on the ones that involve a massive AGB or post-AGB star: white dwarf formation and an electron-capture supernova.

In the case of an energetic eruption where the progenitor survives the explosion, the transients could mark the birth of massive white dwarfs (Thompson et al. 2009). Observations of mass-losing AGB stars show spherically symmetric envelopes, while their descendants (protoplanetary and planetary nebulae) have highly asymmetric and complex morphologies and kinematics. This has been a long standing mystery in stellar evolution for which several mechanisms have been proposed, with magnetic fields, rotation and binaries suggested as primary suspects for breaking the symmetry (e.g., Balick & Frank 2002; de Marco 2009; Sahai 2009 and references therein). In a recent study, Dennis et al. (2008) argue that pPNe outflows may be driven by an explosive MHD launch mechanism similar to the ones discussed in the context of supernovae and gamma-ray bursts. This model seems appealing when applied to NGC 300-OT and SN 2008S – perhaps we are witnessing the launch of the jet in a massive AGB which is shaping a pPN. In this scenario we expect that the pPN now in formation

will become a PN when the central white dwarf left behind ionizes the surrounding gas. The timescale for this is very uncertain, but for a $\sim 8 M_{\odot}$ star it can be of the order of ~ 100 yr (e.g., Stanghellini & Renzini 2000). An interesting prediction of an asymmetric outflow that can be tested with new observations is the detection of strongly polarized light from the transient, which has recently been reported by Patat et al. (2009).

An electron-capture supernova in a massive AGB star has been suggested as a possible mechanism for NGC 300-OT and SN 2008S (e.g., Prieto et al. 2008b; Thompson et al. 2009; Botticella et al. 2009). Two of the main predictions of this scenario that can be tested with late-time observations are the disappearance of the progenitor star years after the explosion and the detection of radioactive ^{56}Ni decay synthesized in the explosion. Botticella et al. (2009) presented detailed photometric and spectroscopic observations of SN 2008S. Their main argument in favor of a supernova explosion as the origin of the transient was presented in the late-time light curve. They found that the pseudo-bolometric light curve at $t \gtrsim 140$ days had a decay slope consistent with radioactive decay of $^{56}\text{Co} \rightarrow ^{56}\text{Fe}$ and inferred the production of $\sim 10^{-3} M_{\odot}$ of ^{56}Ni in the explosion. However, Smith et al. (2009) noted that the late time light curve of SN 2008S was slower than expected from ^{56}Co decay and argued against a supernova interpretation. While a late-time decay slope slower than ^{56}Co is a possibility in SN 2008S, it should be pointed out that slow late-time light curve slopes (compared to ^{56}Co decay) have also been observed in some subluminous type IIP supernovae, including the very well-studied SN 2005cs (Pastorello et al. 2009). Therefore, we think that a supernova explosion origin cannot be excluded from this result alone. The late-time light curve of NGC 300-OT should give very important clues about the possible supernova origin.

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